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4D Dynamic Construction Management and Visualization Software: 2. Site Trial

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Abstract
The performance of any system can only be gauged by practical applications. This paper delineates some insight and experience on the on-site use of a prototype four-dimensional (4D) site management software system for a warehouse superstructure in Hong Kong. It links a three-dimensional model and a construction schedule to furnish visualization of the state of a site at any user-specified date. Site personnel generally view this system as potentially very promising and helpful. The 4D visualization is found to have capability to assist cognitive, reflective and analytical activities of site management. Through this site trial, some limitations of the software are also spotted which consequently lead to enhancement to the system. The prototype model may require a large amount of data input for large projects which lead to large computer files and slow processing speed. Hence, careful implementation of details is required in the planning level for practical 4D simulation modeling. This, however, will not be a long-term problem, given the recent advancement of computer technology.

Keywords 4D Site Management, Construction Planning, Scheduling, Site Trial

Introduction

Conventionally, planners rely on their experience, intuition, imagination and judgment in using the general arrangement drawings and schedules to make resource allocation and site layout decisions. It is hypothesized that an appropriate management support tool, by furnishing a visual representation of the construction site including representation of construction progress of the buildings and status of the prospective site space utilization on any user-specified date, and by allowing interactive manipulation of the site objects and the bar chart schedule, will be of practical help to site management.

This paper describes an on-site trial use of a Four-Dimensional (4D) Site Management Model 4DSMM, which links a three-dimensional (3D) modeling system with a construction time schedule based on Microsoft Project, and outlines the key evaluation findings. The 4D Graphics for Construction and Site Utilization system (GPCSU), intended as an effective aid for better planning and communication amongst site individuals, enables projected visualization of the state of a site. The detailed description of the evolution and development of this prototype visualization system can be referred to Zhang (1996), Chau *et al.* (2002), Chau *et al.* (2003) and Chau *et al.* (2004). The system is currently limited to the modeling of structural elements only. The site state includes finished permanent structural work at that date, the status of the current ongoing construction activities at any specified physical level, the positions of major items of equipment and how the site is being used for such as roadways, storage, assembly areas, etc. The system, as a by-product, can also provide additional management information such as resources requirements on manpower, materials and working space, which are conventionally addressed by algorithmic tools (Son and Skibniewski, 1999; Castro-Lacouture and Skibniewski, 2003).

In order to ensure that 4DSMM is not just developed under a purely research environment, the system development team has spent many short periods on site over the years and many of the system features have been tailored to reflect a diversity of practitioners' inputs. The scope of the on-site study being reported here is limited to the planning at the level of detail relevant to the co-ordination of the structural work of subcontractors and the visualization of completed and ongoing structural work. Through the site trial, both the potentials and difficulties evolved during the study are identified and the implications are then discussed.

The site personnel are very positive about the need for visualization and planning tools like 4DSMM. It is considered that, if the software could better fit the way in which site management actually operates, and processing speeds become much faster in the foreseeable future, then 4D visualization planning and control tools will become very useful and cost effective. Subsequent to this site trial, some enhancements are made to the prototype system in order to pin-point practical considerations brought up by the site personnel. It follows that research and development in this field should continue, with emphasis placed on close collaboration with site practitioners to tailor with their normal practices and the level of details they desire in various circumstances.

The 4DSMM Site Trial

The 4DSMM site management software is tested on a 3-storey warehouse building site – The Tradeport Logistic Centre. The building has the height of a typical 7-storey structure, with 3 storeys of double height with mezzanine floors and also a rooftop structure.

The 3D geometrical model of the superstructure is prepared using AutoCAD, representing all elements floor by floor and based on the construction method and programme proposed by the contractor, and the construction programme model is prepared on MS Project. These two models are duly linked through the 4DSMM application and the entire software package is furnished to the site personnel on an IBM PC (866 MHz Pentium III processor, 128 MB RAM) in the site office. Figure 1 shows a sample screen of data input in Workspace Manager. Figures 2 and 3 show sample screens of this 4-D visualization model on a specified date and the construction schedule prepared on MS Project, respectively. Figure 4 shows a sample screen of this 4D visualization model linking 3D geometrical model with schedule.

In the process, the Senior Planning Engineer is intimately involved and continues to operate the prototype system for planning and decision in real life situation. The following findings are based on the researchers' experiences of developing the models, in conjunction with informal interactions as well as formal discussions with the site personnel. The potential as well as shortcomings that are spotted during the application of the software for site management are presented below.

Utilization Experience

Potential Positive Features in Using 4DSMM

Many positive features have been identified in using 4DSMM. Amongst others, the tool is very effective in furnishing good communication of site use intentions among site personnel. The senior management, client, and site staff are all very impressive on the automatic projection of resource requirements to each site progress condition displayed. In particular, visual simulation facilitates the identification of potential sequence errors and clashes. Furthermore, the simulation model proves flexible to reflect changes in design or work sequences.

The site personnel wholeheartedly appreciate and support the objectives of this prototype computer application and look forward to its realization. The planners currently climb nearby buildings to take photographs of the site at different 3D angles (see Figure 5 for example). They then manually add sketches of the areas/features important for decision making and use highlighting pens for sections that will be completed or need to be discussed. Apart from the task to record the actual progress, the remaining portion of this work could be replaced by 4D simulation such as Figure 6. The site personnel consider it very useful that 4D simulation images could be rotated for viewing from any desired angle, zoomed as required and shared on the computer network, which is impossible by using photographs. The Project Manager stated:

> *This visualization with such detail is very good. We can put it up in meetings to show to people.*

The site personnel stated that the 4D simulation could be strategically used by site management for: progress visualization and presentation, locating equipment such as material hoists, analyzing cranage times, checking access/openings for equipment, storage visualization, co-ordination of subcontractors, identifying possible clashes of trades, planning for resource allocation and utilization and estimating quantities. Since every subcontractor desires to have storage at the closest location, the visualization aspect really makes 4D a good communication tool for relaying intentions to all involved. Moreover, 4D simulation can assist site personnel at brainstorming sessions and discussions about access, storage and sequencing of works.

Previous research by De Saram and Ahmed (2001) has shown that cognitive processes are the most important processes in construction site co-ordination. The 4DSMM application will be useful if it can assist site personnel in situations where cognitive, reflective and analytical skills required by construction project managers test the limits of human capabilities. Otherwise, the effort in setting up the models and continuously updating them as site conditions change may not be justified.

Problems encountered and the corresponding Solutions

In using this new tool, a major problem encountered by the site personnel is the complexity of the tools for inputting the data and the time involved in handling that data. Although the warehouse is a medium scale construction project, the structural work schedule required in the 4DSMM application, still consists of a micro programme of nearly 1600 activities and the AutoCAD 3D model contains some 3500 elements drawn on 56 layers. For instance, the system assumes a concreting activity comprising formwork, reinforcement, concreting and curing and each of these relates to a defined region between construction joints of a concrete element. Similarly, the micro programme for the full building prepared on MS Project results in a large file, which is also slow to process.

For example, when preparing a typical AutoCAD drawing of a wing of a building, the draughtsman may draw each floor and each longitudinal wall as a floor element and a wall element, respectively. However, if the intended concreting work on this wing is to be divided into sections, to suit practical site constraints such as convenient economical pour sizes or locations of expansion joints, each of those elements in the AutoCAD drawings prepared for the GCPSU application has to be split along the construction joint lines. In the building plan shown in Figure 7, for example, if the work breakdown structure (WBS) is to first concrete between Grid Lines 1 to 3, 3 to 5, 5 to 7 and 7 to 9, i.e., on 4 occasions due to the large floor area to be concreted on one occasion, then the slab has to be modeled as 4 pieces for GCPSU in order to relate to the programme schedule. In addition, the external wall along Grid Line A has to be represented as 4 lengths and the external wall along Grid Line E too has to be represented as 4 lengths. The same will apply when drawing internal walls along corridors running through the building longitudinally. It requires additional effort to model structural elements in small pieces when using AutoCAD. The resulting file size may also be large, thus rendering the process slow.

Another disadvantage is that it requires skill, when drawing many small elements, to maintain accuracy than when drawing large elements. 3D AutoCAD does not provide much facilities such as to indicate the centre lines or other guiding lines to help align drawing elements. The draughtsman may have to draw separate guiding lines on another data layer. It is also difficult to move objects accurately in a 3D space. When making 3D drawings it is also not possible to use AutoCAD 2D functions such as 'midpoint', 'end point', 'extend', 'trim' and so on, as AutoCAD is not yet fully developed at the 3D level at that time. Moreover, simple copy and paste will not place the element in the correct 'GCPSU groups', e.g., "first floor beams", "fifth floor walls" and so on, which are GCPSU facilities to group drawing elements according to the WBS.

However, 4DSMM has the capability of linking up to 5 separate AutoCAD drawing (either 2D or 3D) model files with one 'Microsoft Project' construction time schedule. Thus, as an alternative, it is possible to carry out this simulation with a selection of 2D AutoCAD drawings to show the plan, elevations and sections of the building. Because such drawings are available on site, the difficulties of making a 3D AutoCAD model, discussed above, could be avoided. Another major advantage of simulating with 2D views is that site practitioners are used to working with 2D site drawings, which they routinely study to grasp all details therein and save in their photographic memory. They are so familiar with those drawings that they can quickly spot even a minor change when a new revision issued. Previous research by De Saram and Ahmed (2001) indicates that such familiarity enables site practitioners to frequently reflect on the drawings and use their cognitive and analytical skills to identify strategic opportunities and impending problems. Construction progress simulation based on such familiar drawings would greatly help in this important aspect of site management. 3D AutoCAD models, though have the facility of being rotated and viewed from any desired angle and zoomed, may not provide the opportunity of making comparisons with views familiar in photographic memory. Hence, a 2D route remains to be a choice as feasible site simulation systems. Nevertheless, simulation with 2D drawings will preclude the researchers' future expectations of furnishing such associated facilities as computation of quantities for projecting interim measurements and cumulative productivity curve.

Although it is flexible to adapt to changes of design or changes to the sequence of works, additional works, however, are required on the 4D simulation. For example, in Figure 7, if it is decided that Grids 3 to 5 are not to be cast on one occasion but on two occasions separated at Grid 4, then not only does the construction programme need to be changed, but the AutoCAD model too needs to be changed by redrawing the slab and all longitudinal walls between Grids 3 to 5 as two pieces separated at Gird 4.

Fortunately, the new version of AutoCAD 2002 that was released during the project facilitates the conversion of 2D drawings into 3D models. Construction joint lines could be drawn upon the 2D drawings and the 2D elements could be split along these lines. The 2D elements in each section could then be converted to 3D form automatically. This would remove much effort in developing the 3D model on AutoCAD, making the application much easier for use. It is important to note that, at present, 3D modeling can indeed be performed during this experiment. In fact, existing problems of file size, level of details and operation in practice are in a sense secondary, which can be easily alleviated through the development of computing technology in terms of processing speed and data interchange in the near future.

As stated above, much of the data preparation work in using 4DSMM has to be undertaken in AutoCAD and MS Project. Industry practitioners are used to both of these software systems, which is helpful to future success, but the ability to accommodate Primavera and other popular software will also be necessary. The planners at the site suggested that Primavera, which is considered by them to be a more powerful scheduling software; should also interface with 4DSMM. It is agreed that, in general, 4DSMM type applications should interface with any popular software. As such, subsequent to this site trial, enhancement has been undertaken in this direction and interfaces have been developed for a number of popular scheduling software including Primavera.

Another present limitation is the need to create in GCPSU, lists of the construction element groups such as “first floor beams”, “fifth floor walls”, in addition to creating the WBS in Microsoft Project. The WBS based schedule management is not very much in line with site need. The requirement to manually create construction element groups should and can be eliminated, so that:

(a) changes in the WBS automatically cause changes in the MS Project schedule and in the GCPSU list.

(b) changes in MS Project schedule automatically cause changes in the WBS and in the GCPSU list.

The users then have to only work in software applications which are familiar to them. The desirable situation then exists that the models created on AutoCAD and MS Project (or other equivalents) are automatically linked with no further involvement by construction planners or site personnel. This view is taken by the researchers and, subsequent to this site trial, enhancement has been undertaken in this direction and the requirement to manually create construction element groups is now eliminated.

Some time and effort are required in preparing the 3D model and the construction programme. The researchers are not particularly skillful in either AutoCAD drafting or Microsoft Project programming. The approximate time spent in establishing the 4D model comprises:

- 120 man-hours to create the Microsoft Project programme
- 200 man-hours to create the 3D AutoCAD model
- 40 man-hours to link the above two models in GCPSU to form the 4D model

i.e., a total of 360 man-hours or so. The site personnel suggest that a contractor would need an additional staff, especially within the first 3 to 6 months of the project, to create and maintain the 4DSMM experimental model because this level of detail planning at the micro level has to be undertaken by the contractor’s staff using their in-depth knowledge of the construction method and sequence.

Moreover, the GCPSU application is not designed to generate sectional views. The 4D simulation views appear as a cluttered mass of 3D elements which prevent visualization of construction inside the building. This problem is resolved to some extent by using some 56 layers in AutoCAD to draw the superstructure elements and switching on only the layers needed.

Future Directions and Potentials of the Prototype System

The contractor must be the party to the preparation of the construction schedule, but in general the architect could prepare the 3D model at the required level of detail if there is early collaboration between the two parties. The site personnel pointed out that, designers and site planners usually work independently with a low degree of co-ordination, whereas 4DSMM application would be assisted by close co-ordination between designers and site planners. The present weak level of co-ordination can either hinder the application of such software, or else such software itself could, perhaps a bit optimistically, become the means of promoting future co-ordination between designers and site planners.

The 4DSMM application, at its present stage of development, may be more suitable for a *longitudinal* project where work is more sequentially completed and the sequence of work which repeats is fairly tightly defined by the technological logic. For example:

- a tower of residential flats where each floor and set of walls and columns may be constructed/concreted in a fixed sequence which repeats for many floors
- a longitudinal civil engineering project such as a railway line or a highway where, at any cross section, each trade will finish its job (e.g., fixing a precast concrete flyover element, laying sleepers, laying rails) on one occasion

In such projects where the work sequences are repeated, it is worthwhile getting the work sequences thoroughly optimized. The Project Manager commented that more logic driven sites or multi-storey buildings with lots of repetition of floors would be better for this software application, since a saving of even a ½ day per floor is a great contribution to the project. Moreover, the extra effort on creating the 4D model, if required to be undertaken and completed at the beginning of a project when time is extremely tight, is demanding for general practical routine use. The Senior Planning Engineer at the site pointed out that this software application is good if it is a Design and Build project, because the contractor will be involved earlier in the project.

In normal practice, site planners do not prepare so completely at the beginning of a project. They prepare a micro rolling programme for only the few initial weeks. As the work progresses, they would progressively develop micro programmes for a further few weeks at a time, and only where necessary, on the basis of the experience gained in implementing the initial programmes on site. That helps to fine tune the subsequent micro programmes to the site conditions and capabilities of the subcontractors. Exceptions would only be made for specific concentrated sections of the job, where in-depth local planning is required for a particular need, such as ordering equipment or material. For example, in order to calculate the cranage times before ordering the tower cranes for this construction site, the contractor made a micro programme for constructing the superstructure across four bays of a typical floor that requires the erection of precast concrete elements.

In this manner, site management does not invest so much time at the beginning of a contract in making a detailed programme for the whole project that will change as the project unfolds. Planners try to avoid such unproductive double work. In fact, the initial programmes made by the contractor focus on the selection of suppliers, procurement and the logistics of material/component delivery, rather than detailed construction activities such as fixing steel reinforcement and erecting formwork. Even at the broad level of detail, only a portion of the overall construction programme prepared by the contractor for the whole project is on construction activities of the superstructure. Thus the macro level programmes normally prepared at the beginning of a project are not at the level of detail assumed by GCPSU and do not focus much on the construction activity levels of detail needed for subcontractor planning and control.

Thus, it is proposed that the usage of the software should adapt to the usual site practice. There is no absolute necessity to completely create the 4D model for the whole work in details at the beginning of the project duration when time is extremely tight. Thus, a master 4D model at a macro level of detail is established at the inception using GCPSU. A micro rolling programme is prepared for only the few initial weeks or for specific concentrated sections of the job where in-depth local planning is required.

A significant difference between the initial macro programme presented by the contractor to the client and the consultants and the micro programmes eventually given to the subcontractors is that activities on the former programme are naturally much longer in duration and without many overlapping activities. The logic of programmes given to subcontractors is detailed and contains overlaps wherever possible. Thus 4D application has to be adapted so that there are two types of construction programme, at two different levels of detail, which are used in different site management and co-ordination contexts. The higher-level master plan with less detail can provide 4D visualization simulation at a level useful for communication with client and consultants and 4DSMM would be practical now for this purpose. The lower level detailed plan, for effective site communication through visualization of finished work, including the positioning of equipment and detailed use of site space at any selected time, is much more costly to achieve at the present time. It remains a data handling problem constrained by current technology and will have to await advances in transferring and interpreting architects' general arrangement drawings and in computer processing speeds. 4DSMM, nevertheless can be practical now for detailed work, where in-depth local planning is needed for limited parts of a project, or where the project involves a repetitive construction cycle.

Even for detailed level subcontractor planning and control, however, the site personnel opine that 4DSMM requires more detailed input than necessary. They have a view that the display of details such as reinforcement, formwork, concrete and curing may not be necessary. They suggest that, except for those locations where in-depth local planning is required, any activity shorter than one week needs not be shown for large projects. Thus, the timeframe for activities used in the schedule is of an order of 2 weeks and the display of activities such as concreting, which is of an order of a one-day timeframe, may be unnecessary. Planning details should be limited to such as "Construct Columns of Floor N", "Construct Walls of Floor N", "Construct Beams and Slab of Floor N". This requirement, however, can be easily accomplished during the preparation of input data by the user and no enhancement is required on the software itself.

Instead of the simulation of only the progress of structural elements, the site personnel also need simulations at the interfaces of structural elements with services and architectural finishing work. At present, 4DSMM can only be used to view the completion of structural elements at different stages. A1 size color drawings of these images can be printed for mental visualization of the interfaces with services and architectural features. The real co-ordination problems are with the specialty contractors and consultants. In principle, extending the scope of the system beyond the structural aspects is straightforward, but since the structural elements alone lead to huge files, then adding architectural finishing work and services may aggravate the already delicate data handling problems.

Although not true for clients and senior managers, personnel on-site were not really interested in macro level visualization, for example, to answer the question "When will bay N on 2nd Floor start?" because they could visualize this without the help of a computer. The more difficult questions are those that require more complex cognitive, reflective and analytical skills such as:

> *"To bring in the trucks carrying pre-cast elements and to lift them to upper floors, we need to leave out the construction of some small area of the building where it is convenient for both the trucks and the tower crane. How would this left out area clash with the other trades – especially the specialist trades?"*
>
> *"There is going to be this concrete wall [at an odd position]. When is that going to come up? ... We need to know that because it is going to be on the path of many services along the corridor and decisions on their exact paths need to be made on time, as we will need to place sleeves through it!"*
>
> *"When should the services above the ceiling of offices along Grid Lines F-G [specifically] be completed? ... It is imperative because the ceiling subcontractor has to be given a date to commence in that [specific] area."*
>
> *"When could we ask the cladding subcontractor to mobilize? If we get them to start at Grid 15A and proceed towards Grid 1A, will there be a point when they will be out of work?"*

The site personnel would also welcome visualization simulation for either awkward or complex structural elements such as vehicular ramps and staircases. Construction of these elements and their interfaces with architectural works and services require careful co-ordination.

Therefore, until such time as processing speeds are somewhat faster than at present, the focus of 4DSMM application should not be on micro level activities such as:

- Columns at Grids 8 to 10 – Fix Rebar
- Columns at Grids 8 to 10 – Erect formwork
- Columns at Grids 8 to 10 – Pour Concrete

but should be on activities at a macro level of detail and embracing all types of operations and not merely the structural ones. For example:

- Construct Columns at Grids 8 to 10
- Construct Walls at Grids 8 to 10
- Install Chilled Water Lines Along the Corridor at Grid B from Grids 1 to 9
- Install LV Power Lines Along the Corridor at Grid B from Grids 1 to 9
- Install False Ceiling in Offices at Grids 14 to 15

- Install Cladding along Grid A from Grids 1 to 9

Conclusions

This paper delineates the on-site use of a prototype 4D site management software system for a warehouse superstructure in Hong Kong. It is found that 4D simulation can be used strategically by site management for progress visualization, locating equipment, analyzing cranage times, checking access/openings, storage visualization, co-ordination of subcontractors, identifying possible clashes of trades, planning for resource allocation and utilization and estimating quantities. Because it has the potential for good presentations, it will become a good communication tool among site personnel and between site and client and good for assisting construction project managers' cognitive, reflective and analytical processes. The software may facilitate the identification of problems in co-ordination between designers and planners and be useful in promoting such co-ordination in future to the industry's benefit. 4D simulation systems are of significant value on sites, and will be increasingly so with development in information technology. Of course, the additional work involved for day-by-day site planning entails extra man-hour resources to create, maintain and use the 4D model. Hence, in the mean time, its usage should be focused on the macro level of co-ordination between disciplines, where in-depth local planning is needed, and where there is a repetitive construction cycle.

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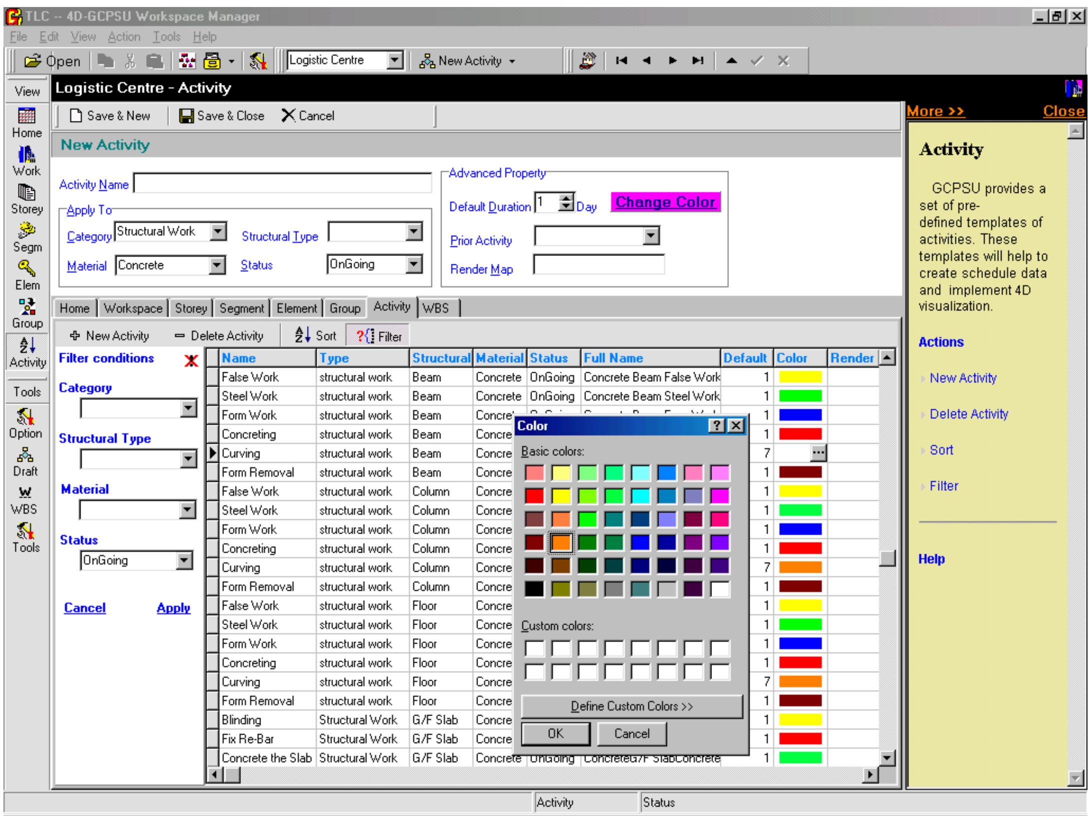


Figure 1. Sample screen displaying input of activity data in Workspace Manager

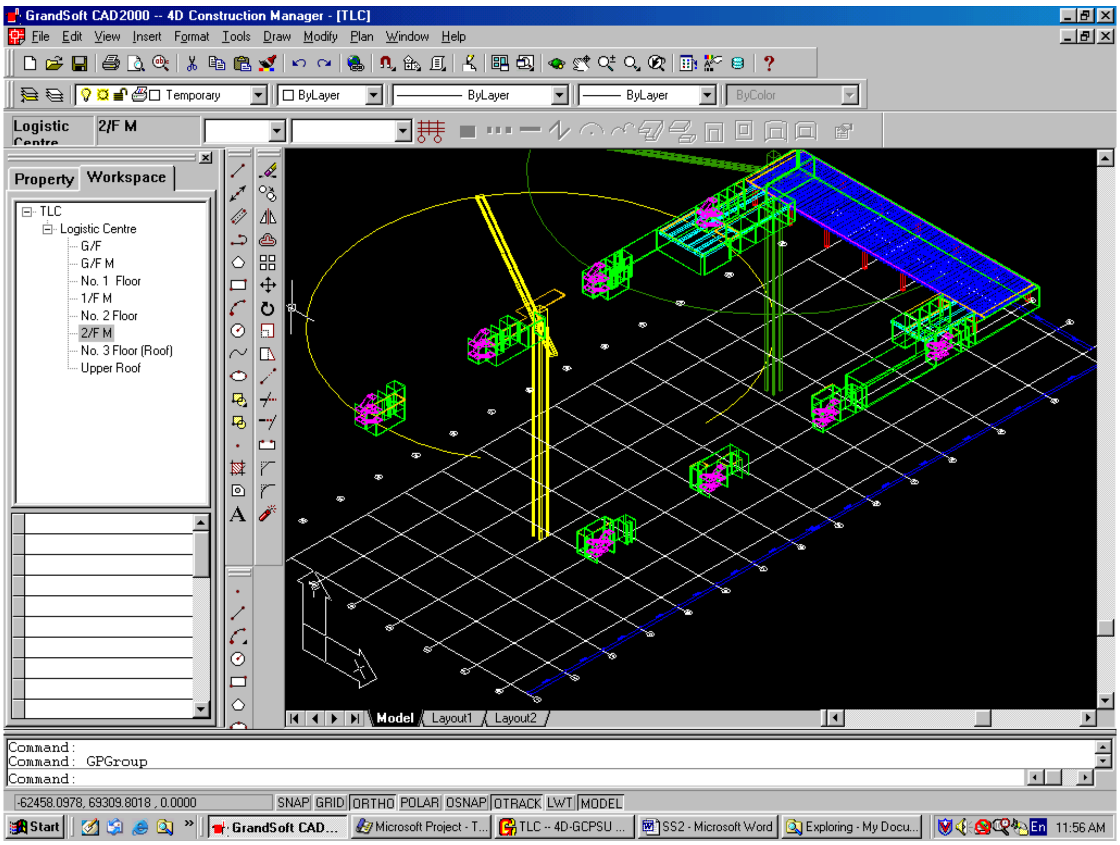


Figure 2. Sample screen displaying this 4-D visualization model on a specified date

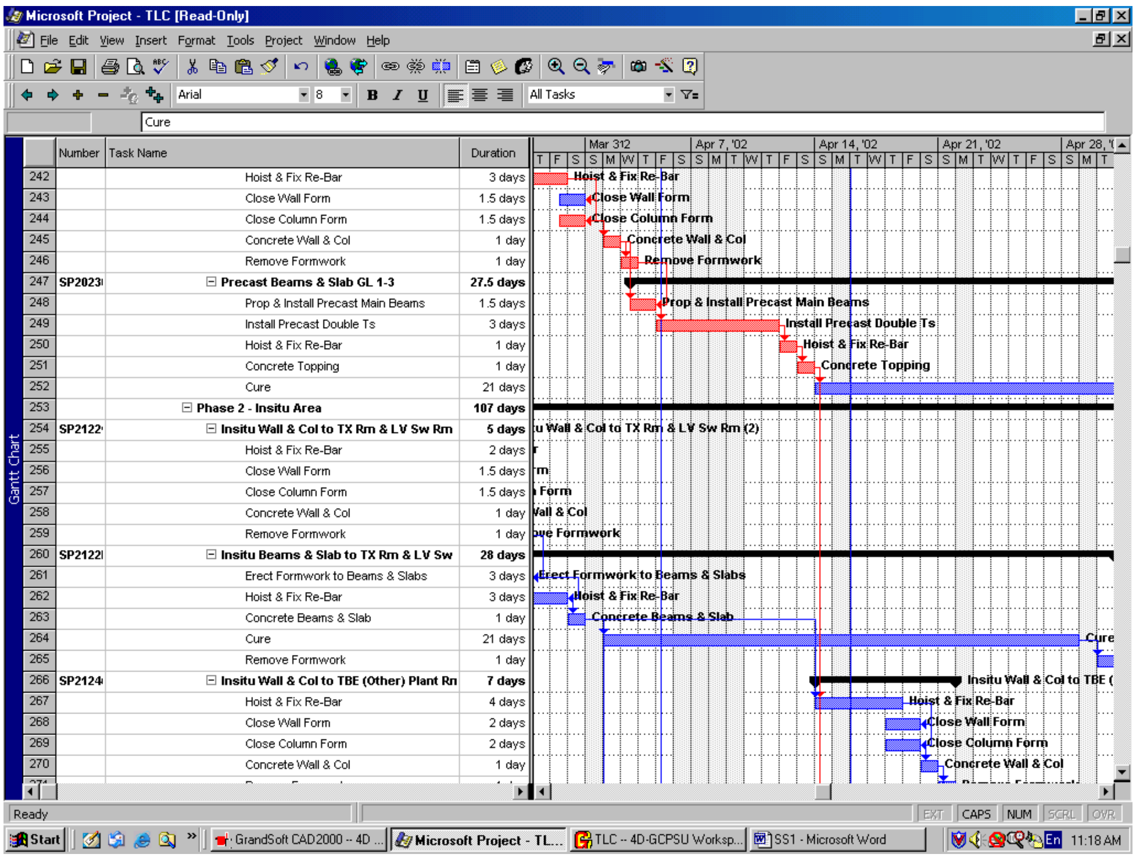


Figure 3. Sample screen displaying the construction schedule prepared on MS Project

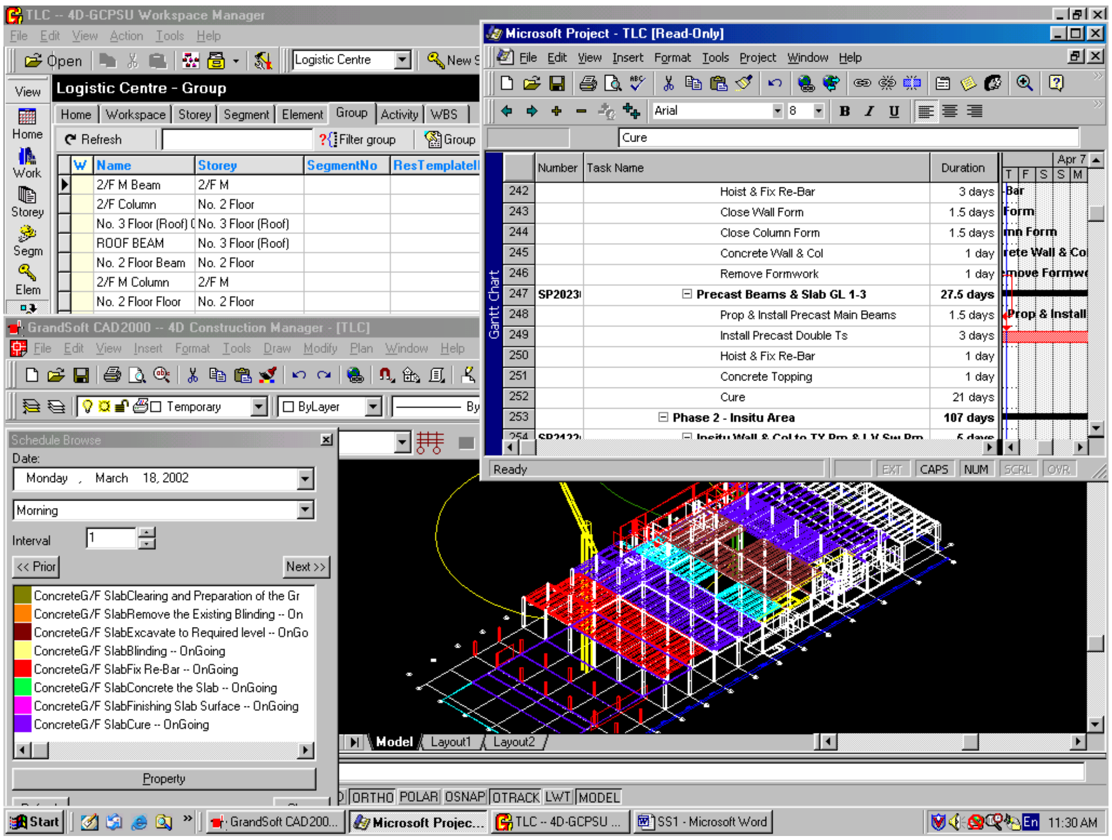
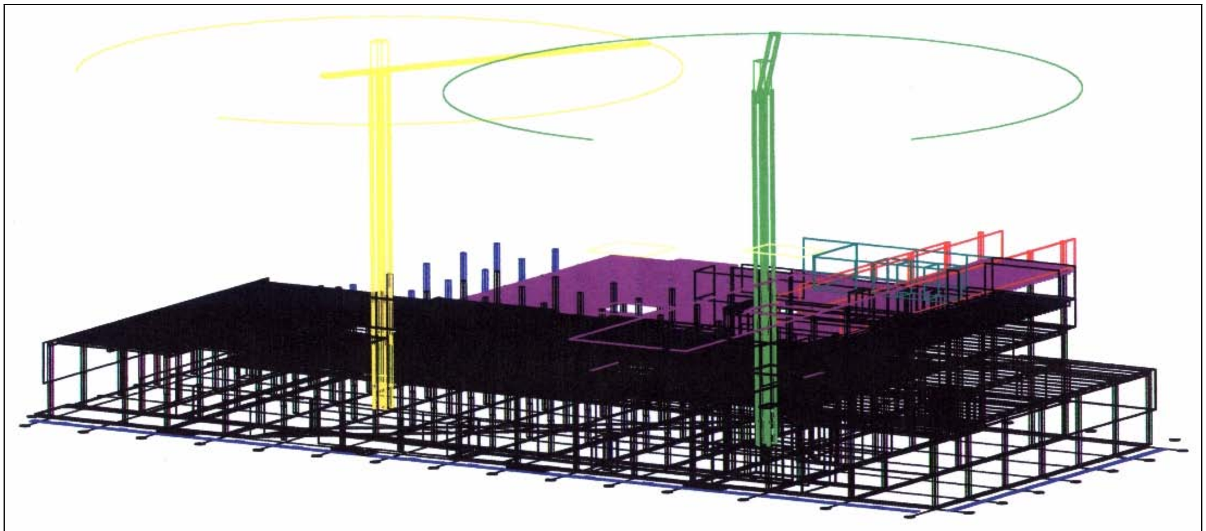


Figure 4. Sample screen of this 4D visualization model linking 3D geometrical model with schedule

Figure 5. A photograph of the building site taken from a nearby mountain



<u>Key to Colours of the Superstructure Elements</u>

Fixing steel reinforcements Closing formwork Concreting
Curing

Removing formwork – also the dimension lines appear in this colour

Superstructure elements completed – also the grid lines appear in this colour

The two cranes appear in the colours for 'closing formwork' and 'concreting' which were the actual colours they were painted in.

Figure 6. Simulated visualization of the state of the building site on the same day as above

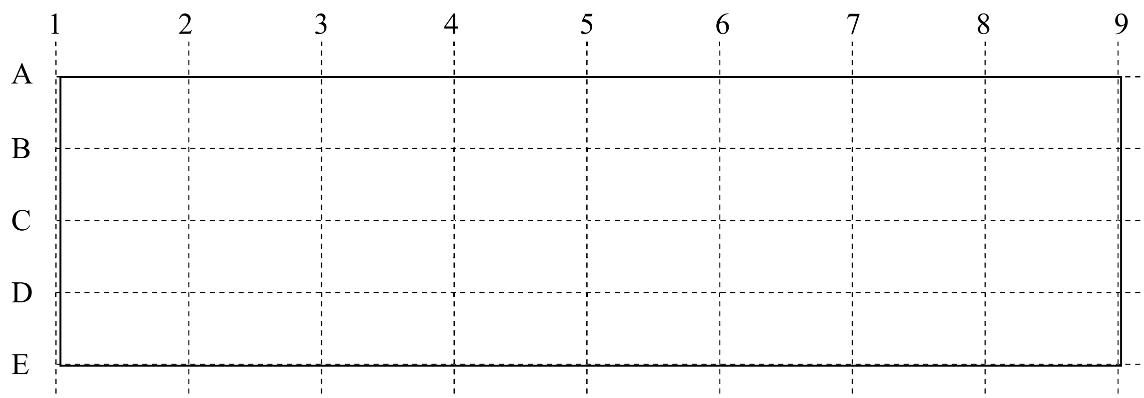


Figure 7. Plan View of a Building